Neutrinoless double beta decay: Valence neutrons in ^{130}Te and ^{130}Xe

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Basics on the Nature of the Neutrino

Dirac theory was developed for electrons: spin ½ particles that are ***charged.*** Their anti-particles had to have opposite charge and so are distinct.

Neutrinos are neutral, they do not have electric charge and their 'handedness' *(that appeared to be an intrinsic property as long as neutrinos had no mass)* changes under time-reversal.

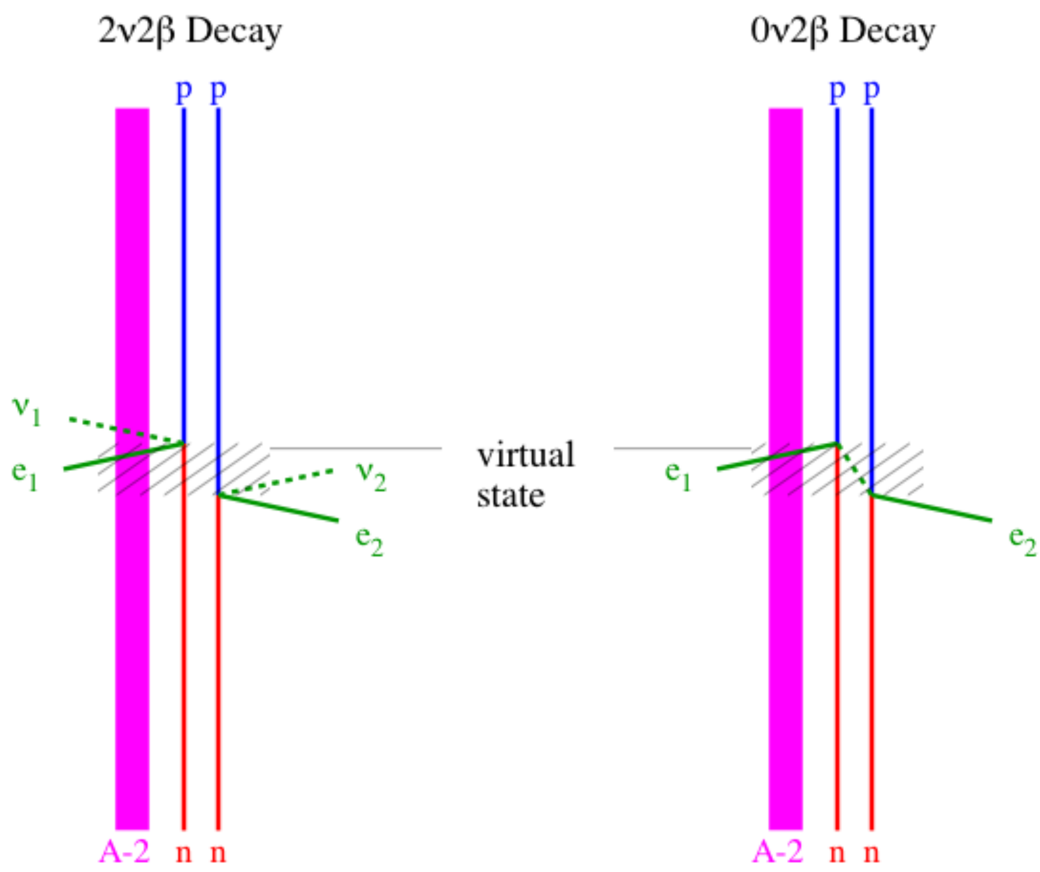
Since neutrinos ***do*** have mass, Majorana may have been right when he suggested ~75 years ago that neutrinos are their own antiparticles. The Standard Model has nothing to say about it, it can accommodate neutrinos either way *(lepton number conservation is an assumption, not a prediction).* This is physics at a more fundamental level.

The only experiment we have to test this very basic issue about elementary neutral fermions is the observation of a nuclear process: **neutrinoless double beta (0ν2β) decay**. If this is observed, it will yield the absolute value of the rest mass of the electron neutrino ***as long as the nuclear structure aspects are well understood.***

The ($2\nu2\beta$) decay mode is just two regular beta decays, the momentum transfer is small, and the rate depends on the virtual excitation of a few, low-lying 1^+ states in the intermediate nucleus.

The ($0\nu2\beta$) mode **is different**, it also goes through virtual states in the intermediate nucleus, but the virtual momenta of the neutrinos is large, and they can thus access ***all*** particle-hole excitations up to more than 50 MeV and essentially ***all*** multipolarities.

If all virtual modes are equally accessible, ***closure*** can be used, and the intermediate nucleus will not matter. Only the properties of the **initial** and **final** states come in.



The rate of ($0\nu2\beta$) depends on the ***mass of the neutrino***. ***If*** the process ***is*** observed, it may provide the **absolute neutrino mass.** But the **nuclear structure** needs to be under control.

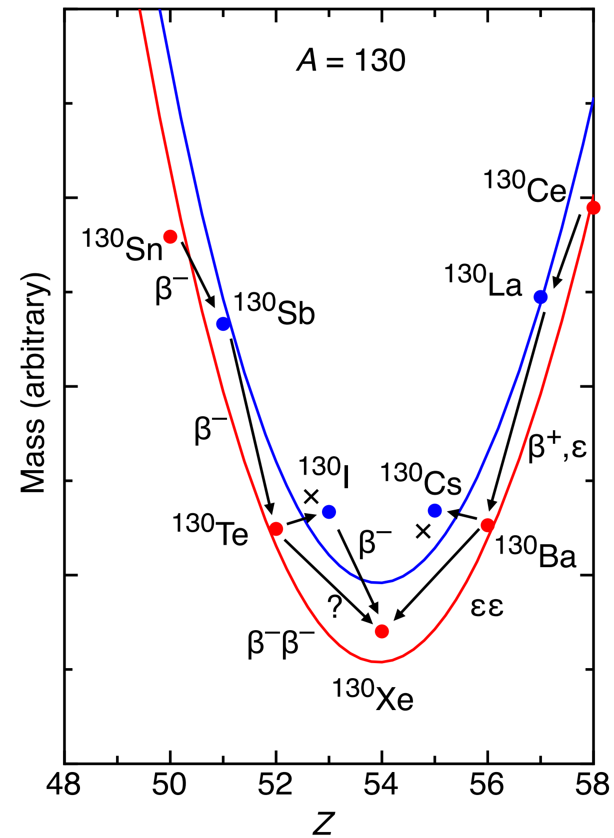
Basics on 0ν and 2ν Double Beta Decay

A certain number of even-even nuclei are unstable against double beta decay. For instance, $_{52}\mathrm{Te}^{130}$ cannot single-β decay to $_{53}\mathrm{I}^{130}$ because the latter is heavier by **0.43** MeV, but ***can*** decay by emitting 2β-s into $_{54}\mathrm{Xe}^{130}$ with **2.51** MeV.

Two-neutrino decay a 'normal' process, that has been observed. It is a five-body decay, with two electrons and two antineutrinos emitted. The half life is about $6\mathrm{x}10^{20}$ years, about **one decay per hour** per kg of tellurium.

If neutrinos are indeed their own anti-particles, then the ***neutrinoless*** (0ν2β) decay mode will be ~$10^{26\text{-}27}$ years, a **<1 count a year** per kg. The CUORE experiment with 750 kg of tellurium is under way. The 2ν and 0ν modes are very different and not simply related.

We try to constrain the calculations of the rate by carefully measuring the properties of ^{130}Te and ^{130}Xe.



So, what **can be done experimentally** to check the reliability of calculations? It is up to nuclear physicists to find ways to calibrate this potential yardstick.

The empirical calibration of a process that was done for other nuclear processes *(such as simple beta decay, electromagnetic decay, or reactions)* cannot be done when, at best, we will only have one or a very few cases.

QRPA is used in most calculations, but it has not been too successful in reproducing specific matrix elements. It assumes BCS for the ground states.

The $0\nu 2\beta$ decay changes a pair of (0^+) valence neutrons to a pair of valence protons.

1) We can map out the microscopic **valence populations** and the **change** between initial and final states by one-nucleon transfer.

2) We can measure the validity of the assumed **BCS** description of **correlations** in the two g.s. wave functions with two-nucleon transfer.

Have done this for ^{76}Ge decay: PRL **101,** 112501 (2008), PRC **79** 021301 (1979).

^{130}Te is one of the nuclei being used to search for this mode in the CUORE experiment. This nucleus has 52 protons and 78 neutrons, and decays to ^{130}Xe, with 54 and 76. The open orbits at the Fermi surface are

$0h_{11/2}$, $2s_{1/2}$, $1d_{3/2}$, $0g_{7/2}$, and $1d_{5/2}$

but for neutrons, this close to N=82, only the first three orbits are significant.

One-nucleon transfer reactions map out the ***occupations*** of valence states, if the measurements are carefully done, by application of the **Macfarlane-French sum rules**.

For the consistency of this method, see recent work in the vicinity of another candidate system: see work on ^{76}Ge and recent test on Ni: PRL **108,** 022501 (2012).

Targets & Measurements

Tellurium is no problem – targets are made easily by evaporation onto a thin (~50 μg) carbon foil.

Xenon is a gas – other solutions are needed: gas cell, or a frozen target. Our Berkeley collaborators built a **frozen target**. Difficulty: xenon would not freeze on thin carbon; a much thicker (~360 μg) diamond foil had to be used. Beam was kept below 10 nA for deuterons, and 2-5 nA for alphas, and even then target had to be monitored.

Absolute target thicknesses were obtained from Rutherford scattering, in the ***same*** geometry (collimation, apertures, beam integrator) as the rest of.the measurements. *(8-MeV deuteron scattering at 20° and 20-MeV α scattering at 25°)*

Neutron adding

^{130}Te(d,p)^{131}Te, ^{130}Xe(d,p)^{131}Xe at E_d = 15 MeV, also (α,^{3}He) E_α = 50 MeV

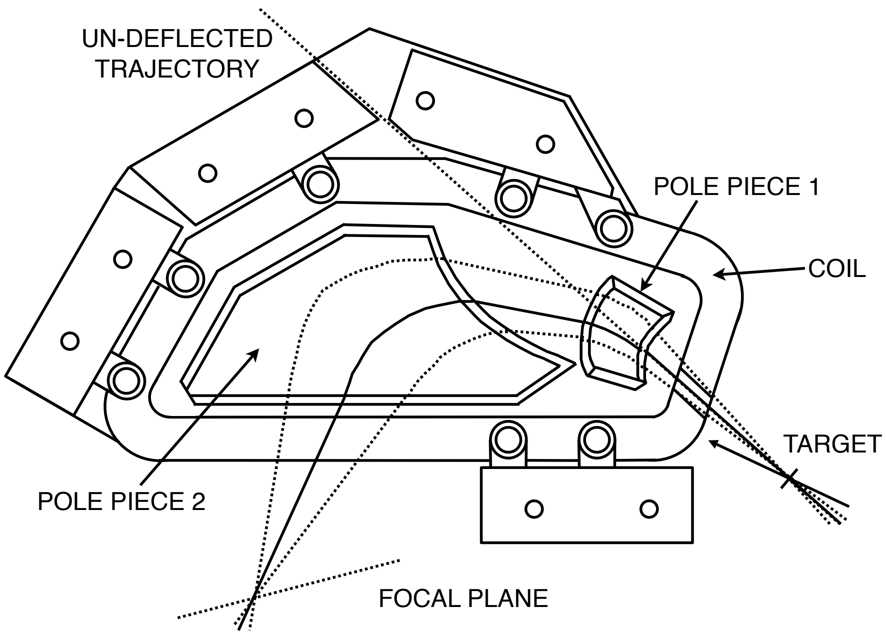
the same measurements were also made on ^{128}Te and ^{132}Xe for consistency checks.

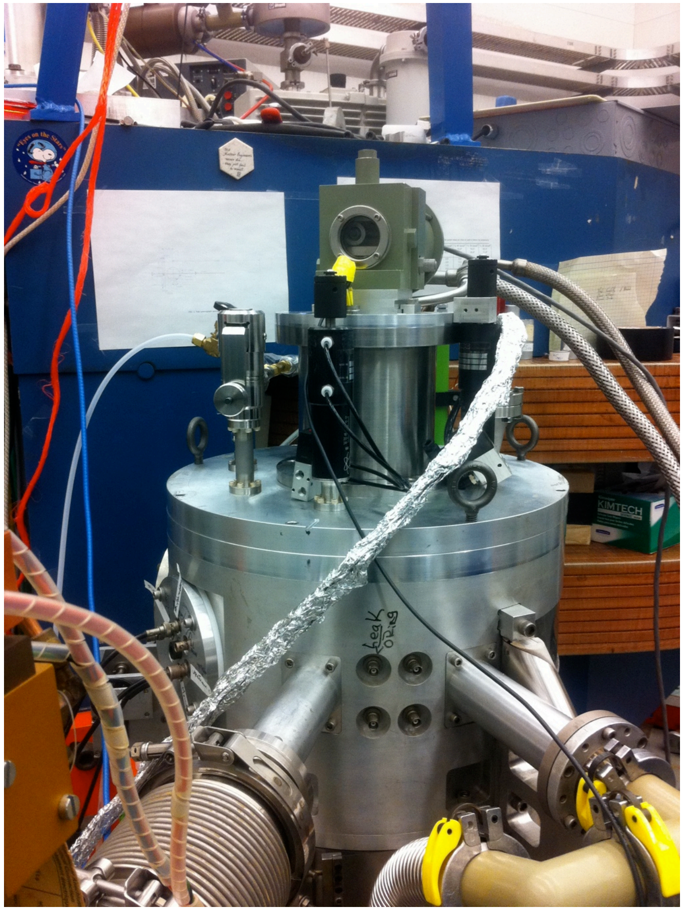
Neutron removal: (p,d) and (^{3}He, α) were also measured and summed – to obtain normalization of the absolute spectroscopic factors.

Run at YALE Tandem

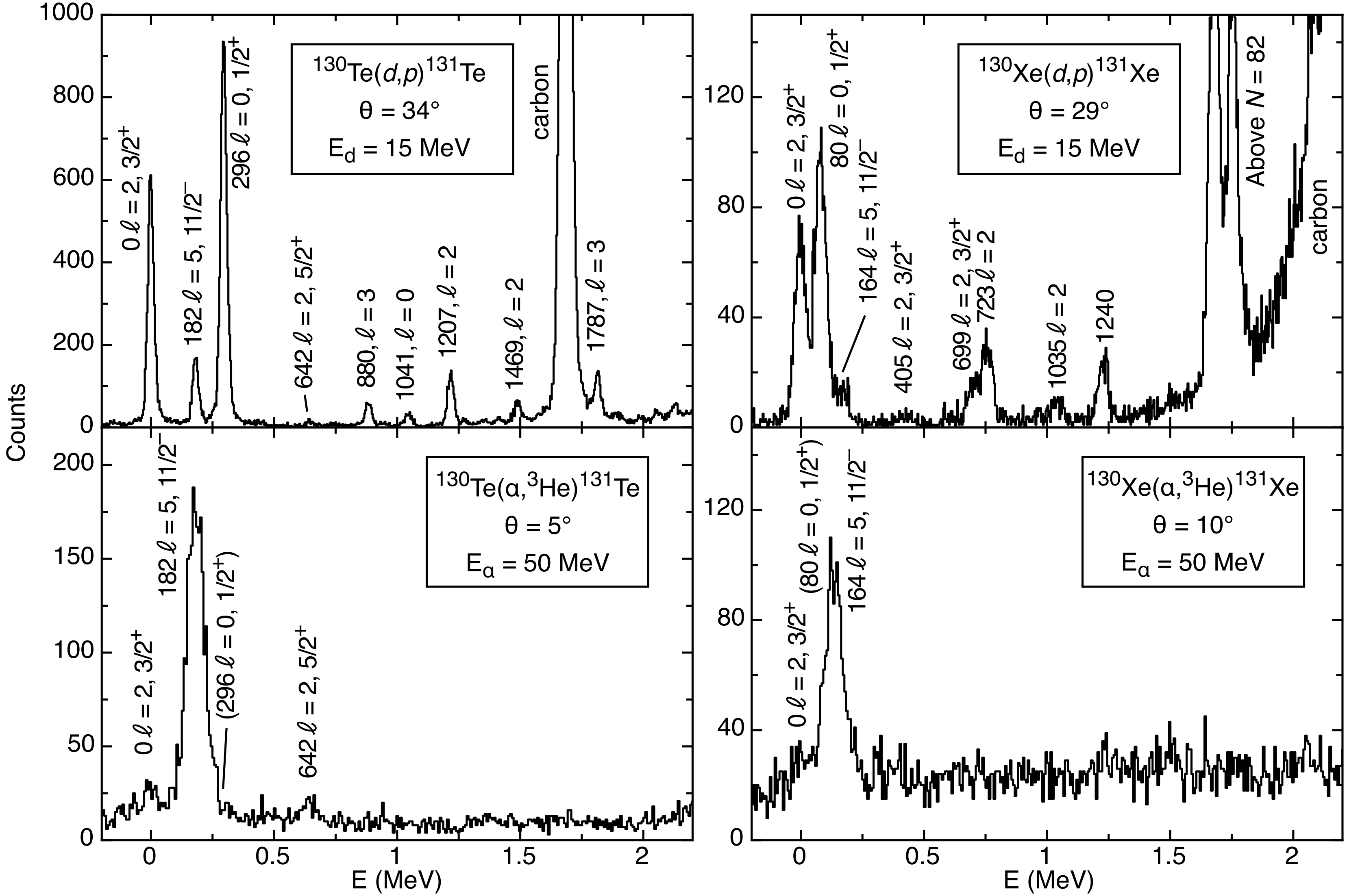
in last weeks of its life

+ Enge Spectrograph





The Berkeley cryogenic target



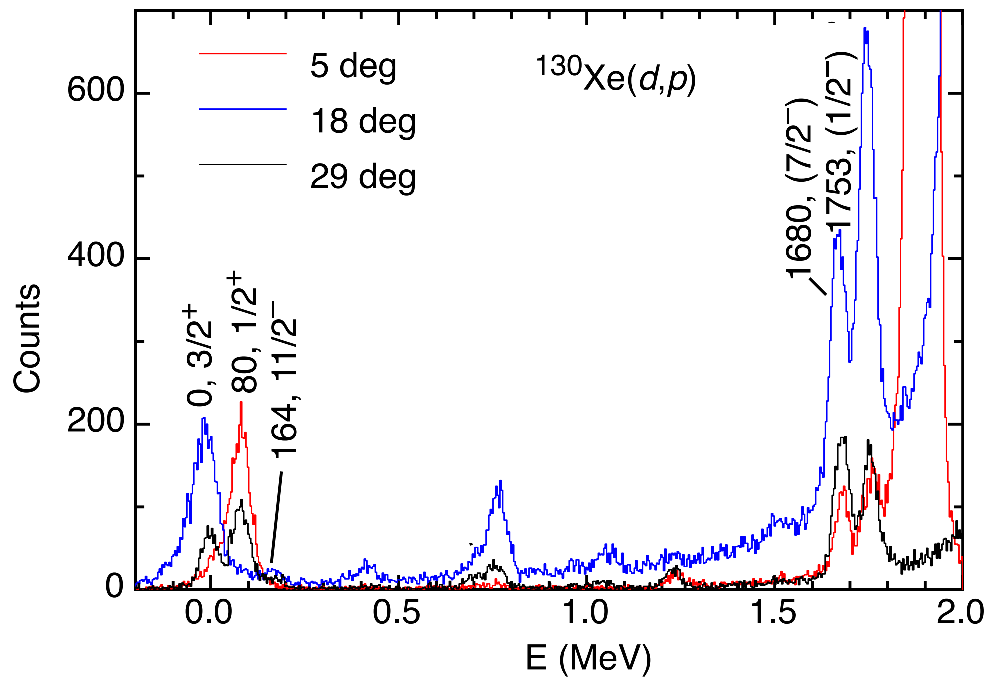
(d,p) and (α,^{3}He) spectra for Te and Xe.

Note resolution is worse for alphas and for Xe targets.

Since ^{130}Te and ^{130}Xe are just 4 and 6 neutrons short of N=82 only the $0h_{11/2}$, $1d_{3/2}$, and $2s_{1/2}$ show vacancies in neutron adding reactions. The (α,^{3}He) data provided information on the $11/2^{-}$ states, several angles were measured in (d,p) to sort out the rest.

Most of the strength is in a closely-spaced triplet near the g.s., though the l=2 strength is somewhat fragmented. Orbits beyond N=82 are above ~1.6 MeV.

DWBA, done ***consistently***, yields accurate relative spectroscopic factors.



Normalization N was obtained by requiring the summed spectroscopic factors (occupancies + vacancies) to add up to (2j+1) = **2.0, 8.0, 12.0** for **$2s_{1/2}$, $0g_{7/2}$, $0h_{11/2}$** respectively. Values of $N_{d,p}$ for ^{128,130}Te were 0.574±0.010.

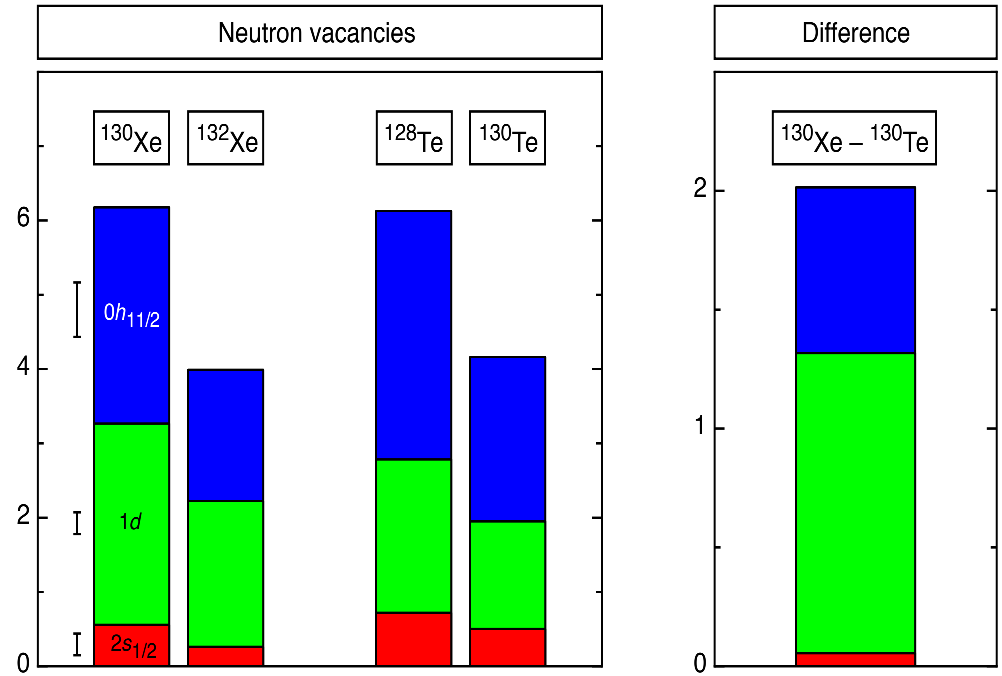
With this $N_{d,p}$ (*and $N_{\alpha,3He}$=0.810 from comparing the l=5 (α,^{3}He) and (^{3}He,α)*) one gets the vacancies:

	N=76	N=78
Expected	6.0	4.0
Te	6.13	4.16
Xe	6.16	3.99

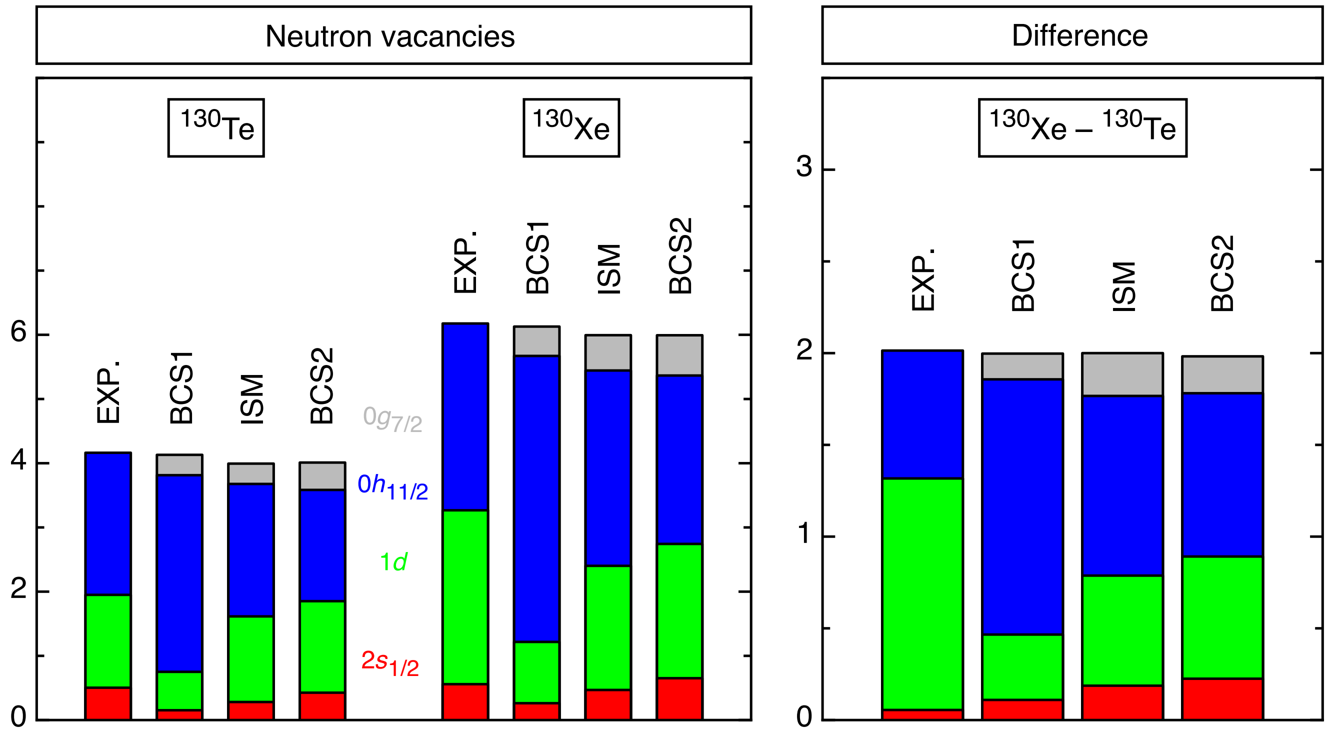
The vacancies are an independent check of how meaningful this is (e.g. ±0.15 neutrons).

N.B.

1. There is **no** sign of *any* **vacancy in $0g_{7/2}$**.
2. The **change in $2s_{1/2}$** is **negligible**; it **cannot participate** appreciably in the decay.



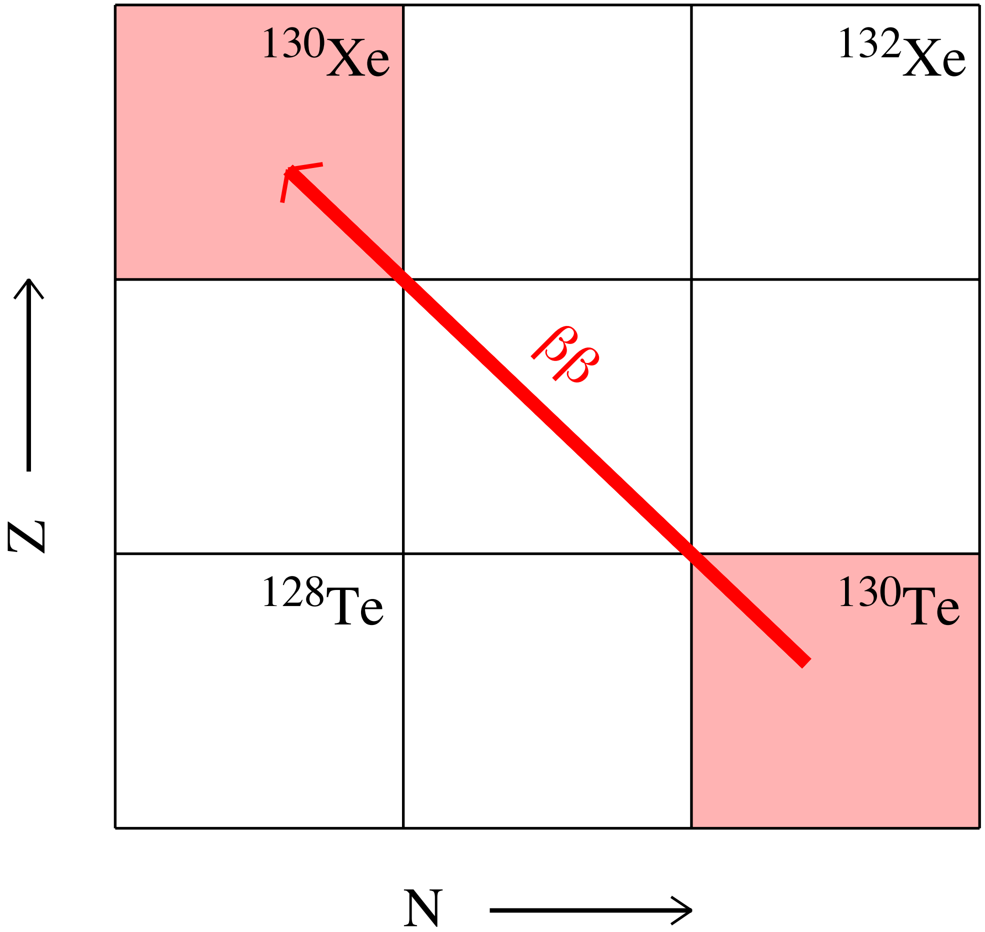
There are several calculations:



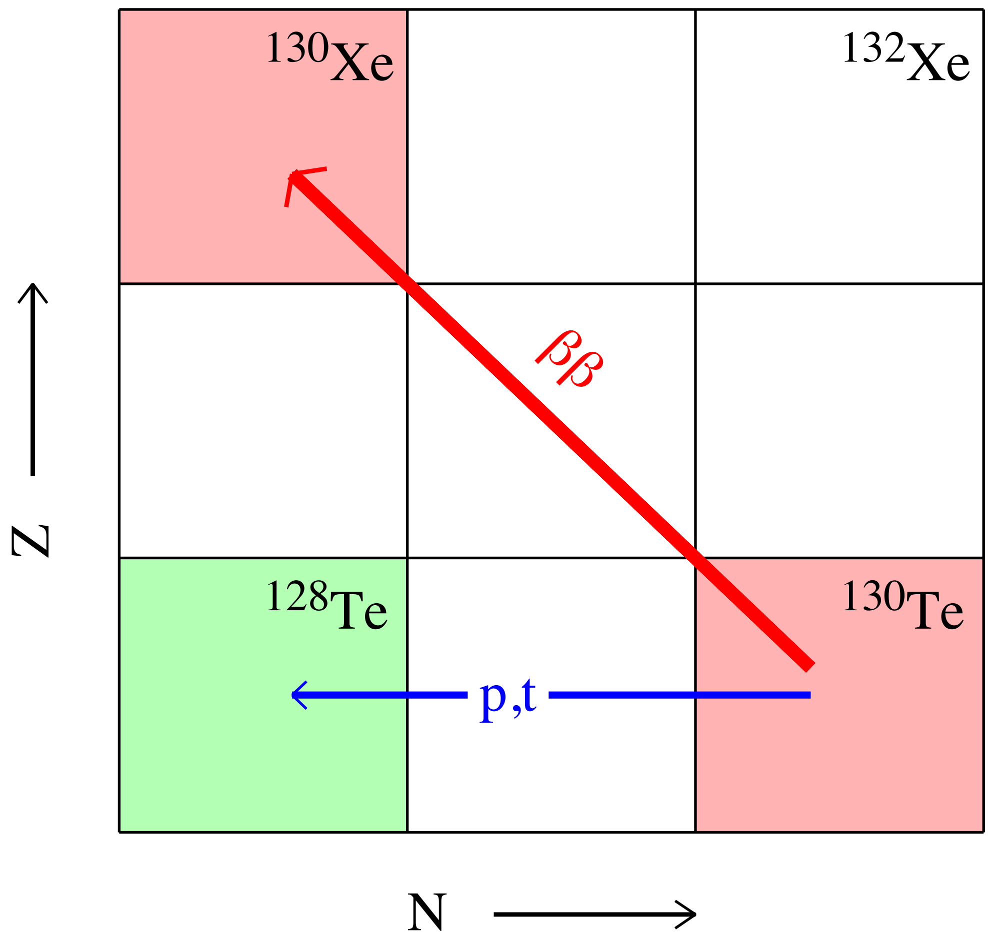
All the calculations predict **more $0g_{7/2}$ and $2s_{1/2}$** participation than our data indicate. The change in 1d (mostly $d_{3/2}$) is **measured to be larger** than in the calculations.
Such differences, in the case of ^{76}Ge, caused substantial changes in the decay rates.

BCS: Suhonen & Civitarese, NPA **847**, 207 (2010). ISM: Poves et al. PRL **100**, 052503 (2008)

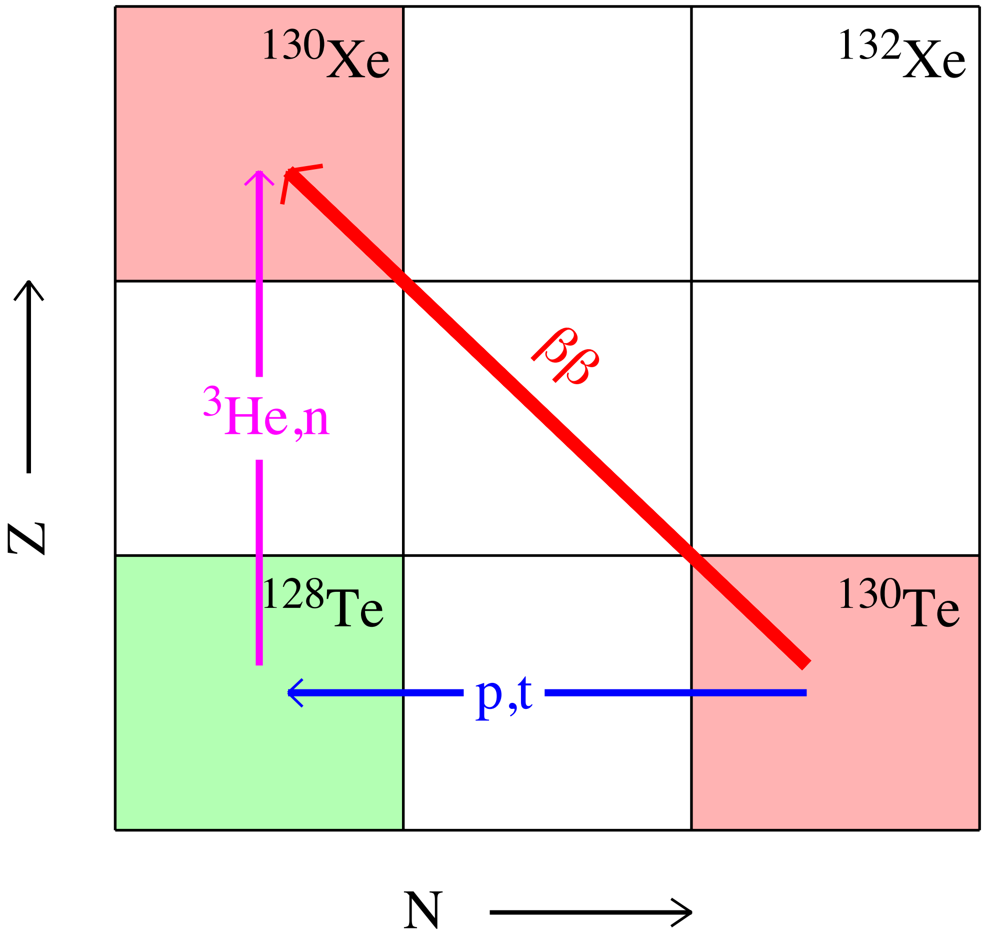
The Role of Pair Correlations in 0ν2β decay



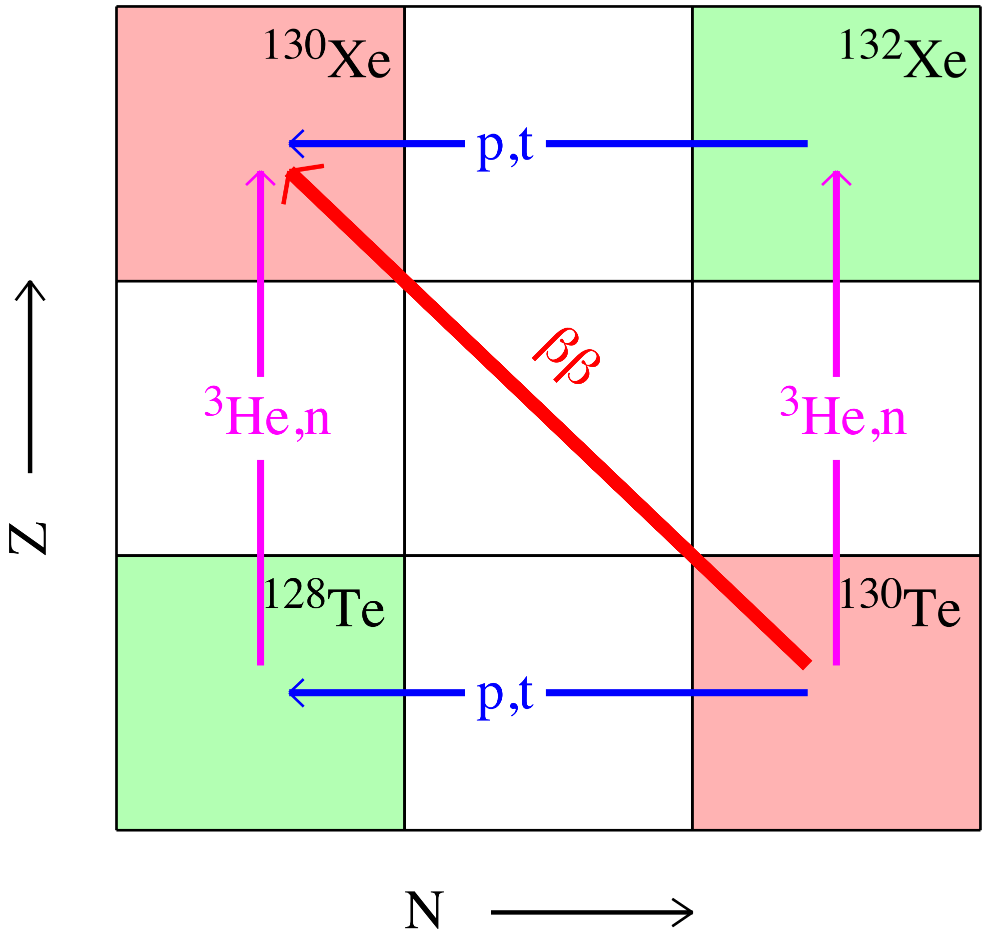
Destruction of a zero-coupled neutron pair



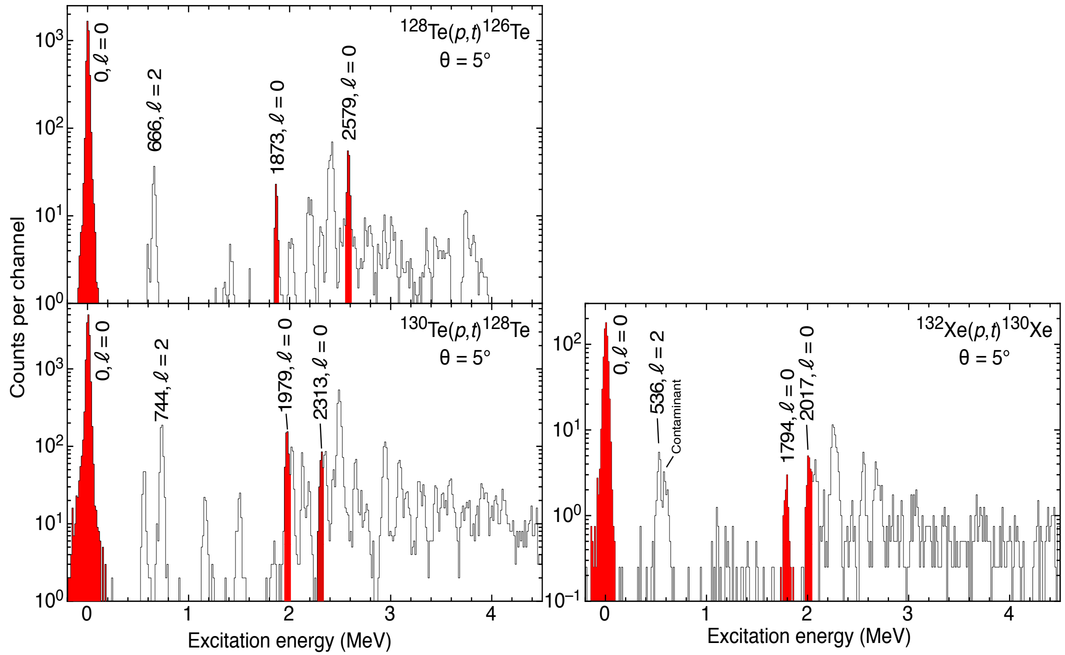
Creation of a zero-coupled proton pair



QRPA assumes BCS; $0^+ \to 0^+$ pair transfer probes BCS assumption.



Pair transfer as a probe of BCS correlations among 0^+ pairs of nucleons has been well known for ~50 years. A large g.s. cross section with a forward peak in the neutron-pair adding (p,t) or removing (t,p) reactions is the characteristic signature.



The g.s. peak is strong, and there is ***no*** excited 0^+ state seen in the p,t cross section, with more than ~2% of the ground state, in tellurium or xenon.

A **BCS** sea, indeed seems to be a **good** description for valence **neutrons** in the ground states of these nuclei.

T. Bloxham *et al.*, Phys. Rev. C **82**, 027308 (2010)

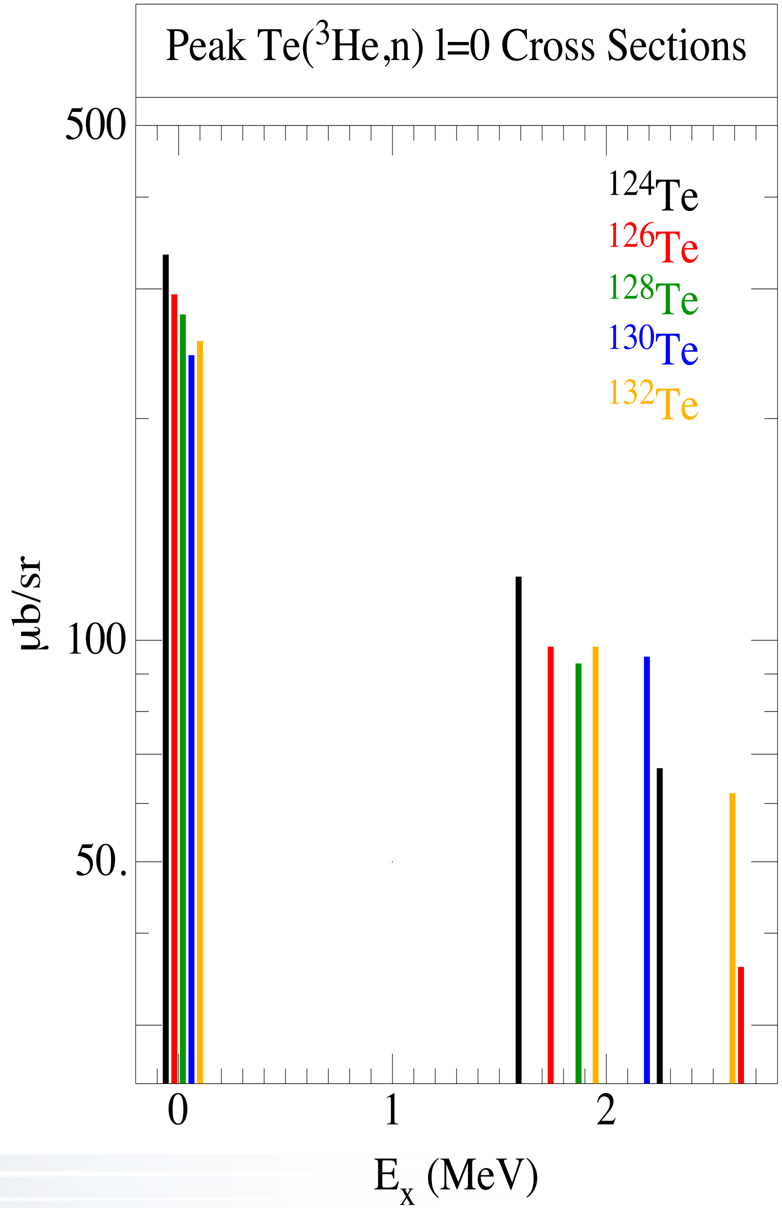
But in **proton-pair adding** Te(^{3}He,n)Xe, an excited 0^+ state at ~2 MeV excitation was seen with 30-40% of the g.s. strength in all the xenon isotopes. Alford et al. Nucl. Phys. A **323,** 329 (1979).

Is this a proton "pairing vibration" associated with the Z=64 subshell?

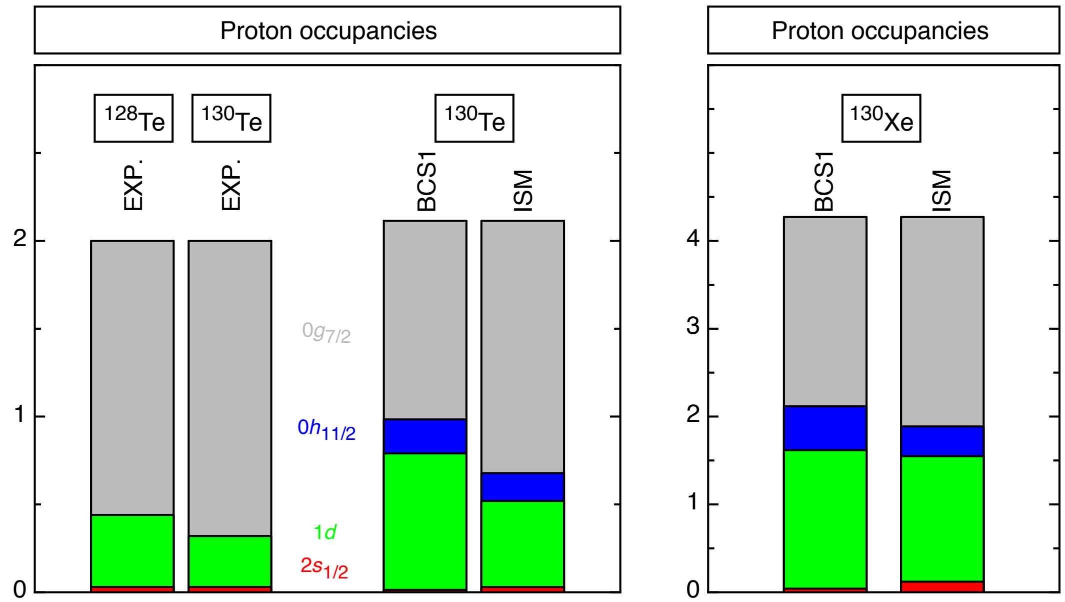
In any case, it indicates a **significant deviation from BCS** correlations in the ground state **for protons**. *(not all proton orbits between Z=50 and 82 participate in the ground states)*

QRPA *assumes* BCS – and the consequence of a more limited BCS space (more limited correlations) is unclear.

The consequences have ***not*** been explored within QRPA (or shell model), but perhaps the loss of phase space in proton-pair adding may be important.



As to **proton valence occupations,** there are only fragmentary measurements from the 1960-s, and only for tellurium.



There are significant differences between the earlier data and QRPA. There is no evidence of occupancy of the $0h_{11/2}$ and the $2s_{1/2}$ has less than the calculations. Perhaps this is also indicative of the $Z = 64$ sub-shell gap.

New experiments are proposed at Osaka on proton occupancies in tellurium and xenon.

This is why I am talking here; Ben Kay is defending the proposal this week at RCNP.

Experiment: R. L. Auble *et al.*, Nucl. Phys. A **116**, 14 (1968). QRPA calculation: Suhonen & Civitarese

Conclusions

Neutron orbit occupancies for ^{130}Te, Xe were measured, and found to be significantly **different** from those in calculations.

Neutron-pair correlations are consistent with BCS assumptions for the valence orbits.

Proton occupancies not yet measured, some indications of inconsistencies, from earlier work – further experiment planned.

Proton-pair correlations are **not consistent** with the simple BCS premise of QRPA; significance of this is unclear at present.

More work is needed experimentally and theoretically to put this nuclear structure tool for important fundamental physics on a more solid foundation.

It is up to our community!